

On the Wind from the SMC B1V Companion to PSR J0045-7319

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ABSTRACT

We report on multi-frequency radio timing observations of the unique binary pulsar PSR J0045–7319, the only known radio pulsar in the Small Magellanic Cloud. Observations made at epochs near periastron and apastron, when the pulsar was at distances from its B1 V star companion of ~ 4 and ~ 40 stellar radii, reveal no significant frequency-dependence of the observed pulse arrival times, implying a 3σ upper limit to variations of the integrated electron density along the line of sight of $\Delta N < 0.9 \text{ pc cm}^{-3}$. Using simple geometric arguments we infer a uniquely direct 3σ upper limit to the ionized component of the B star mass-outflow of $\dot{M} < 3.4 \times 10^{-11} (v_\infty/v_{\text{esc}}) M_\odot \text{ yr}^{-1}$. This is the first constraint on a main-sequence B star wind in the SMC and provides evidence in favor of the predicted metallicity dependence of models of radiation driven winds in luminous stars.

Subject headings: pulsars: individual: PSR J0045–7319 – Magellanic Clouds – binaries: general – stars: mass-loss – stars: atmospheres of – early-type stars

1. Introduction

Observational constraints on wind velocities and mass-loss rates of luminous, massive stars are important for testing models of radiation driven winds. In such winds, the mass outflow is a result of the absorption of photospheric radiation by UV metal lines in the outer atmosphere. Mass loss from hot, luminous stars is relevant to their evolution, interaction with the interstellar medium, and hence galactic evolution. However, measurements of wind parameters, especially mass-loss rates, are made difficult by large uncertainties, both random and systematic, as well as by the necessity for relying on models of the winds to interpret the observations, (see Kudritzki & Hummer 1990 for a review). observational tests of radiation driven wind theory include modeling spectra of individual stars, and comparing trends in the wind properties of a large sample of stars with parameters like effective temperature, luminosity, and metallicity.

PSR J0045-7319 (PSR 110042-73) is a 0.926 s radio pulsar in a highly eccentric binary orbit with a B1 V star (Kaspi et al. 1994, hereafter Paper 1). It is the only known pulsar in the Small Magellanic Cloud (SMC). This association is assured both by the observed line-of-sight integrated electron density or dispersion measure $DM \simeq 105 \text{ pc cm}^{-3}$, since models of the galactic electron distribution account for no more than $\sim 25 \text{ pc cm}^{-3}$ along the line of sight (Taylor & Cordes 1993), as well as by the apparent luminosity (16 mag in V) of the B1 V star that lies within the $\sim 1''$ positional error box determined via pulsar timing. Astrometric, spin, and orbital parameters from two and a half years of radio timing observations reported in Paper 1 are given in Table 1.

Recently, Bell et al. (1995) have detected Doppler shifts of the B1 V star's optical absorption lines, making this the first dual-line binary pulsar, and unambiguously confirming the nature of the pulsar's companion. Those observations determined the mass ratio in the system, 6.3 ± 1.2 , which, for a pulsar mass of $M_p = 1.4 M_\odot$, implies a B star mass of $M_c = (8.8 \pm 1.8) M_\odot$, and an orbital inclination angle of $i = 44^\circ \pm 3^\circ$. From the effective temperature of $(24000 \pm 1000) \text{ K}$ and the luminosity of $1.2 \times 10^4 L_\odot$, Bell et al. (1995) deduced a radius for the companion B star of $R_c = (6.4 \pm 0.7) R_\odot$.

The periastron separation, given by $s_{\min} = a_p(1-e)(1+M_p/M_c) = (3.7 \pm 0.5)R_c$, is determined by observations under the assumption that $M_p = 1.4 M_\odot$, while the apastron separation, $s_{\max} = a_p(1+e)(1+M_p/M_c) = (35.2 \pm 5.1)R_c$. Despite the close approach of the pulsar to the companion at periastron, no eclipse, anomalous scattering, nor any DM increase has been observed at any orbital phase (Paper 1). Indeed the 3σ upper limit on DM variations obtained in Paper 1, 3.2 pc cm^{-3} , implied a mass loss rate significantly below that predicted on the basis of standard empirical mass-loss rate formulae (deJager, Nieuwenhuijzen & van der Hucht 1988; Lipunov, Postnov & Prokhorov 1995). Nevertheless, low-level yet significant deviations from a simple Keplerian orbit, as evidenced by the high RMS timing residual reported in Paper 1 (see also Kaspi et al. 1995a), suggested the presence of 1 DM variations just below the level measurable using only the spectral baseline available from observations at a single radio frequency with a finite bandpass.

To search for the effects of dispersion due to orbital-phase dependent DM variations from the B1V star wind, we have conducted multi-frequency radio observations of PSR J0045–7319 at several epochs near and away from periastron.

2. Observations and Results

All observations were made using the 64-m radio telescope at [sic] Parkes, Australia. A total of 471 arrival times were obtained at center radio frequencies 436, 660, and 1520 MHz from June 22 through July 25, 1994. Cryogenically-cooled systems receiving orthogonal linear polarizations were used at all three observing frequencies, with a coaxial feed allowing simultaneous observations at 436 and 1520 MHz. The signals were down-converted to an intermediate frequency, filtered in a multi-channel filter-bank, detected, and band-limited. At 1520 MHz, the filter-bank consists of $2 \times 64 \times 5$ MHz filters; at 660 MHz it consists of $2 \times 128 \times 250$ kHz filters, and at 436 MHz the filter-bank contains $2 \times 256 \times 125$ kHz filters. After summing of the polarizations, the signals were sampled at 4.5 ns intervals using one-bit digitization and recorded on magnetic tape. Offline, the data were folded modulo the predicted topocentric pulse period, and average profiles—were cross-correlated with high signal-to-noise templates. Arrival times were recorded and analyzed with the

standard pulsar timing software package TEMPO (Taylor & Weisberg 1989) using the JPL1, DE200 solar system ephemeris. Arrival time uncertainties are in the range 0.5–3 ms for these observations, and are limited in precision by the average profile signal-to-noise ratios, typically 10–20,

The epochs of the observations, the number of observations at each frequency, the corresponding orbital phases ϕ , the pulsar/B star separation s , and the observed DM values with 1σ uncertainties are tabulated in Table 2. Periastron is defined to be at $\phi = 0.0$. The uncertainties on the tabulated separations are uniformly 14%. The DM values are plotted as a function of time in Figure 3, where the finite duration of the measurement interval is indicated with a horizontal error bar, smaller than the size of the point for all but one epoch. The vertical dashed lines indicate periastron and apastron. The solid horizontal line is the mean value of DM, $(1.05.08 \pm 0.30) \text{ pc cm}^{-3}$, in agreement within uncertainties with the value measured in Paper 1 using only the 436 MHz bandpass. The reduced χ^2 of the DM's is 1.76; with 7 degrees of freedom, the probability of exceeding this value is 10%. We note that a large contribution to the observed χ^2 comes from the epoch right before periastron, at which the DM is *lower* than the mean by 1.7σ . Furthermore, the mean value of the 1 DM measurements near periastron is slightly lower than that near apastron, though consistent within measurement uncertainties. Thus we conclude that we see no statistically significant evidence for any variation in DM as a function of orbital phase, and place a 3σ upper limit on DM variations of $\Delta \text{DM} < 0.9 \text{ pc cm}^{-3}$.

3. Discussion

The translation of the above upper limit on orbital-phase-dependent DM variations to a limit on the amount of ionized mass-loss from the B star is straightforward. The definition of DM is

$$\text{DM} \equiv \int_0^d n_e(l) dl, \quad (1)$$

where d is the distance to the source from Earth, n_e is the electron density, and l is the line-of-sight distance measured from the pulsar to Earth. Conservation of mass can be expressed via

$$\dot{M} = 4\pi r^2 n_e(r) m_p v(r), \quad (2)$$

where r is the radial distance from the B star surface, m_p is the proton mass and $v(r)$ is the wind speed. Here we assume hydrogen is the dominant element in the wind, that it is fully ionized, and that \dot{M} is constant. We adopt the standard velocity law for radiatively driven winds,

$$v(r) = v_\infty (1 - R_c/r)^\beta, \quad (3)$$

where v_∞ is the terminal velocity and $\beta=0.5$ (Castor, Abbott & Klein 1976; Pauldrach, Puls & Kudritzki 1986).

Using Equations 2 and 3 to determine $n_c(r)$, we integrate through the atmosphere of the companion star from the pulsar to Earth along 1 according, to Equation 1. Using the expression

$$r^2 = s_{\min}^2 + l^2 - 2s_{\min}l \sin \varphi \sin \theta \quad (4)$$

at periastron and an analogous expression at apastron, we integrate numerically to obtain

$$\dot{M} = \frac{4\pi v_\infty m_p}{R_c I} \Delta DM, \quad (5)$$

where I is the unitless difference between the periastron and apastron integrals. Using the 3σ upper limit $\Delta DM < 0.9 \text{ pc cm}^{-3}$, we have $\dot{M} < 3.4 \times 10^{-11} (v_\infty/v_{\text{esc}}) M_\odot \text{ yr}^{-1}$, where $v_{\text{esc}} = \sqrt{2M_c G/R_c} = 724 \text{ km s}^{-1}$ is the companion's escape velocity, with $(v_\infty/v_{\text{esc}})$ likely in the range 1-3 (Abbott 1982; Bjorkman & Cassinelli 1993). For a velocity law with $\beta = 1.0$ we have $\dot{M} < 2.9 \times 10^{-11} (v_\infty/v_{\text{esc}}) M_\odot \text{ yr}^{-1}$.

The upper limit on the mass-loss rate from the B1V companion to PSR J0045-7319 is considerably smaller than what is expected from empirical mass-loss rate-luminosity relations (Garmany et al. 1981; Garmany & Conti 1984; Van Buren 1985; deJager, Nieuwenhuijzen & van der Hucht 1988), which predict mass-loss rates in the range 10^{-9} - $10^{-8} M_\odot \text{ yr}^{-1}$ for a star of this luminosity and effective temperature. However empirical relations are heavily weighted by those stars (O stars and luminosity class I and II stars) for which mass loss can be observed easily via standard methods (e.g. P Cygni profiles, H α line profiles, radio free-free emission). Hence those relations likely overestimate mass-loss rates of less luminous main-sequence B stars, for which wind observations using standard techniques are difficult. Nevertheless Snow (1982) was

able to observe the winds of several Galactic main-sequence B stars and found mass-loss rates to be in the range $(0.15\text{--}2.5) \times 10^{-9} M_{\odot} \text{yr}^{-1}$ for stars of similar spectral type and luminosity to the B1V under study here. These mass-loss rates are still larger than the upper limit for the companion to PSR J0045–7319, unless its terminal velocity is surprisingly large.

The low mass-loss rate measured for the companion to PSR J 0045–7319 is likely a result of the low metallicity in the SMC. The metallicity dependence in the models for the mass loss of luminous stars is a prediction of the theory of radiation-line driven winds, since the accelerative force is obtained from the radiative momentum absorbed by metal lines near the peak of the stellar continuum (Lucy & Solomon 1970; Castor, Abbott & Klein 1976; Abbott 1982; Pauldrach, Puls & Kudritzki 1986; Kudritzki, Pauldrach & Puls 1987). This prediction has been the motivation behind considerable observational effort to compare luminous stellar winds in the Galaxy with those in the LMC and SMC, where the metallicities are known to be smaller, $Z \sim 0.3$ and 0.1 times the solar value Z_{\odot} respectively (e. g. Kudritzki, Pauldrach & Puls 1987). A number of authors have noticed a distinct contrast in the wind strengths of Galactic and SMC O stars, with evidence for significantly smaller \dot{M} and v_{∞} for SMC O, B1, and BII stars, even given the large scatter and uncertainties in the measured values (Walborn 1977; Hutchings 1982; Burhweiler, Parsons & Wray 1982; Garmany & Conti 1985; Prinja 1987; Garmany & Fitzpatrick 1988; Walborn et al. 1995). This is generally interpreted as evidence in favor of a metallicity dependence. ~'bus, the upper limit on the mass-loss from the SMC companion to PSR J0045–7319 provides additional, independent evidence for the metallicity dependence, the first of its kind for a main-sequence B star. Indeed, using the radiative driven wind model outlined by Kudritzki, Pauldrach & Puls (1987), with $T = 24000$ K, $R_c = 6.4 R_{\odot}$, $\log g = -4.0$ and adopting a SMC metallicity $Z = 0.1 Z_{\odot}$, the model-predicted mass-loss rate and terminal velocity are $\dot{M} = 8 \times 10^{-11} M_{\odot} \text{yr}^{-1}$ and $v_{\infty} = 1536 \text{ km s}^{-1}$ respectively, slightly larger than our upper limit (Kudritzki, personal communication). However Puls et al. (1995) point out that wind theory significantly overestimates both \dot{M} and v_{∞} for early main-sequence B stars.

The evidence presented here in favor of a metallicity dependence of radiatively driven wind theory is admittedly based on a single SMC Still. Radio timing observations of a large sample

of OB/pulsar binaries, both in the SMC as well as in the Galaxy, could provide a new, powerful, and uniquely direct method of studying the winds of luminous stars. Indeed the mass-loss rate of the B star binary companion to the radio pulsar PSR B1259-63, the only other known pulsar/main-sequence star binary, has also been constrained using techniques very different from those traditionally used for studying stellar winds (Johnston et al. 1995a; Kaspi et al. 1995b). Searches for more OB/pulsar binaries are currently underway.

These results strongly suggest that the origin of the pulsar's timing residuals is dynamical. Although timing noise is common in pulsars, the qualitative properties of the residuals for PSR J0045-7319 are unprecedented (cf. Arzoumanian et al. 1994; Johnston et al. 1995 b). A model in which the spin-induced quadrupole moment of the B star results in classical apsidal advance and spin-orbit coupling has been proposed (Jais, Bildsten & Kaspi 1995) but further timing observations will be necessary before the model can be tested.

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Table 1: Astrometric, Spin, and Orbital Parameters for PSR J0045–7319 from Kaspi et al. (1994).

Right Ascension, α (J2000)	00 ^h 45 ^m 34.9 ^s ± 0.2 ^s
Declination, δ (J2000)	−73° 19′03.2″ ± 0.8″
Period, P	0.9262758349(1) s
Period Derivative, \dot{P}	4.465(7) × 10 ^{−15}
Epoch of Period	MJD 48964,2000
Orbital Period, P_b	51.16926 (2) days
Projected semi-major axis, $a_p \sin i$	174.235(2) lt s
Longitude of periastron, ω	115.236(2) [°]
Eccentricity, e	0.80798(1)
Epoch of Periastron	MJD 49220.3817(1)
R.M.S. timing residual	7.4 ms

Table 2: Epochs of DM Measurements.

MJD	N	N	N	ϕ	s	DM	σ_{DM}	
	1520	660	436		(R _c)	(pt. cm ⁻³)	(pc cm ⁻³)	
49524,7-49525,1		1	0	5	0.947--0.955	10.3-9.1	105.59	0.25
49525 .7-49526.0	0	1	2		0.967--0.973	7.1-6.1	105.21	0.36
49526 .7-49527,1	0	2	3		0.986--0.995	4.1-3.8	104.56	0.27
49527,7-49528.1	0	4	4		0.005--0.014	4,8-6,1	104.86	0.13
49528 .6-49530.1		1	1	5	0.025--0.053	7.7--12.2	105.08	0.16
49530 .7--49531.1	2	1	3		0.064--0.072	13.8-14.8	105.00	0.09
49531 .7-49532.0	1	0	2		0.083--0.089	16.2-16.9	105.22	0.20
49558 .6-49559.0	3	1	3		0.609-0.618	34.0-33.9	105.13	0.11

Fig. 1.- Observed DM versus time. The solid horizontal line represents the mean DM, (105.08 ± 0.30) pc cm $^{-3}$. The vertical dashed lines indicate the epochs of periastron ($\phi = 0$) and apastron ($\phi = 0.5$). Horizontal error bars represent the interval over which the 1 DM measurements were made, but are smaller than the size of the points for all but one observation.

